

Enhanced generation of oxidative species and phenol degradation in a discharge plasma system coupled with TiO₂ photocatalysis

Huijuan Wang^{a,c}, Jie Li^b, Xie Quan^{a,*}, Yan Wu^b

^a Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), School of Environmental and Biological Science and Technology, Dalian University of Technology, Dalian 116024, China

^b Institute of Electrostatics and Special Power, Dalian University of Technology, Dalian 116024, China

^c College of Life Science and Technology, Xiaogan University, Xiaogan 432000, China

Received 14 October 2007; received in revised form 5 February 2008; accepted 6 February 2008

Available online 12 February 2008

Abstract

In this paper, the streamer formed during a pulsed discharge process was used as a lamp house to induce the photocatalysis of TiO₂ in a pulsed discharge plasma system. A synergistic effect of plasma and TiO₂ photocatalysis was revealed through a comparison of the generated amounts of oxidative species ($\cdot\text{OH}$, $\cdot\text{O}$, H_2O_2) and phenol decomposition in the plasma system with and without supported TiO₂. A spectral analysis of oxidative radicals such as $\cdot\text{OH}$ and $\cdot\text{O}$ identified a higher emission intensity of the radicals in the plasma/TiO₂ system than in the plasma alone system. Both the H_2O_2 concentration and the phenol degradation in the plasma/TiO₂ system were higher than those in the plasma alone system. Furthermore, higher energy efficiency of phenol decomposition and total organic carbon (TOC) removal was achieved in the plasma system coupled with TiO₂ photocatalysis. Moreover, the streamer was proved to be in existence by measuring the power in the systems of plasma alone and plasma-photocatalysis system. This coupling process can be further studied to identify and exploit the existence of streamers in plasma channels.
© 2008 Elsevier B.V. All rights reserved.

Keywords: Discharge plasma; Pulse streamer; TiO₂ photocatalysis; Synergistic effect; Oxidative species; Phenol degradation

1. Introduction

As one of the potential advanced oxidation processes (AOPs), non-thermal plasma production during discharge in the liquid or hybrid liquid–gas phase has long been exploited for water and wastewater purification, since the investigation of pre-breakdown phenomena of discharge in aqueous solutions was first reported by Clements et al. in 1987 [1]. Owing to its virtue of producing in situ oxidative species for decomposing toxic compounds, its operational simplicity (realized under the conditions of an ambient temperature and pressure), its variable reactor configuration, and its good-performance degradation of low-concentration organic compounds, this discharge technique has been of great interest in the field of environmental protection for the past two decades [2–12].

Because of the potential industry applications of pulsed corona discharges, many studies have been carried out using

discharge plasma for biorefractory contaminants removal. In these researches, the chemical effects of active species ($\cdot\text{OH}$, $\cdot\text{H}$, $\cdot\text{O}$, O_2^- , $\cdot\text{HO}_2$, H_2O_2 , O_3) produced in plasma channels have always accounted for most of the decomposition of organic compounds in wastewater [13–19]. By contrast, the physical effects formed during the pulsed discharge process, such as strong electric fields, streamer (including UV light), electro-hydraulic cavitations and supercritical water oxidation, have received little attention.

Heterogeneous photocatalysis of TiO₂ is also a promising AOP for wastewater treatment, attracting researchers since Honda studied the decomposition of water molecules on TiO₂ electrodes in 1972 [20]. When the surface of TiO₂ (particles or films) is irradiated with light of wavelengths shorter than ~ 387 nm, the generated holes (h^+) and electrons (e^-) can react with ambient water molecules to produce reactive species (O_2^- , $\cdot\text{OH}$). The $\cdot\text{OH}$ radicals and h^+ themselves serve as the pivotal species aiding in assuring the degradation of organic compounds in the photocatalytic system.

The spectral analysis of Sun et al. [15] proved that there was a discharge radiant in far ultraviolet to near infrared spectral

* Corresponding author. Tel.: +86 411 84706140; fax: +86 411 84706263.

E-mail address: quanxie@dlut.edu.cn (X. Quan).

ranges in the pulsed corona discharge system, as well as intensified light during the discharge process. Therefore, the streamer spectra in the ultraviolet region may excited the photocatalytic activity of TiO_2 . Lukeš et al. [21] and Hao et al. [22] similarly proved the enhancement of contaminants degradation in a pulsed discharge plasma process in combination with TiO_2 powder.

The present work investigates the synergistic effect of plasma and TiO_2 photocatalysis on oxidative species generation and organic compound degradation, by establishing a hybrid liquid–gas phase pulsed discharge system coupling with TiO_2 photocatalysis, streamer is used as a new lamp house to induce the photocatalysis of supported TiO_2 in the plasma system. Coupling the two AOPs should permit higher energy efficiency and further practical applications.

2. Experimental

2.1. The plasma-photocatalysis reaction system

Fig. 1 displays a schematic diagram of the plasma-photocatalysis (plasma/ TiO_2) reaction system. The system consisted of a pulsed high-voltage power supply and a reactor, with parameters of the pulsed discharge system the same as those of our previous work [23]. A cooling system maintained a constant temperature throughout the experiment. The pulse peak voltage, the pulse frequency, and the capacitance were kept at 21 kV, 50 Hz, and 4 nF (the corresponding energy was 538 mJ per single pulse, which is the integral value of the wavelength of the product of the voltage and current waveforms with single pulse) in all reaction processes. A digital oscilloscope (Tektronix TDS2024), a high-voltage probe (Tektronix P6015A) and a current probe (Tektronix P6021) were used to monitor the discharge parameters. A PlexiglasTM cylinder (75 mm diameter and 100 mm length) served as the reactor vessel. The electrode system inside was with seven-needle-to-plate geometry, and the electrode was made of stainless steel with a distance (d) 15 mm.

2.2. Spectral analysis system

A spectrum testing system within the interim reaction system (Fig. 2) detected the emission intensities of $\cdot\text{OH}$ and $\cdot\text{O}$.

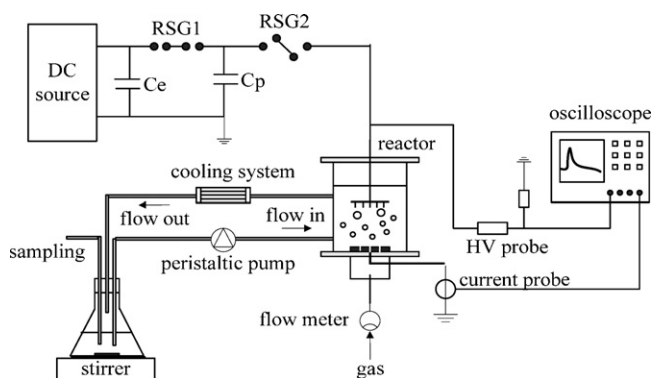


Fig. 1. Schematic diagram of the experimental system.

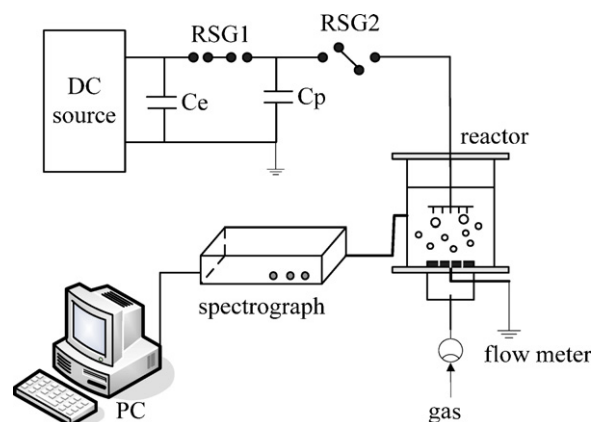


Fig. 2. Schematic diagram of the spectral analysis apparatus.

The spectral plot was recorded by a spectrograph (Inspectrum 300, Acton Research Corporation) combined with a computer. The head of an optical fiber 1 mm in front of a quartz window (5 mm in diameter) and parallel to the tips of needle electrodes collected the light signal. The light signal was detected from the gas phase plasma in water. The operational parameters of the spectrum system used to record the spectral plot were adjusted to a 1200 mm/g grating and a 500 μm slit width.

2.3. Materials

All reagents used in this study were of an analytical grade and were used as received; analytical eluents were HPLC grade. All experiments were conducted in deionized water at room temperature. A sol–gel process deposited photocatalytic TiO_2 films on soda-lime glass beads of 5–6 mm particle size [24]. The formed precursor solution reached $\text{Ti}(\text{OC}_4\text{H}_9)_4:\text{C}_2\text{H}_5\text{OH}:\text{H}_2\text{O}:\text{NH}(\text{C}_2\text{H}_4\text{OH})_2 = 1:26.5:1:1$ in molar ratio. All experiments used a supported TiO_2 film photocatalyst prepared through eight dipping–lifting processes. X-ray diffraction (XRD) analysis identified the prepared TiO_2 particles about 6 nm in diameter, and scanning electron microscopy (SEM) indicated a uniform TiO_2 film on the glass beads.

2.4. Experimental method

Phenol at an initial concentration of 100 mg/L (an initial pH of about 7) was chosen as the target contaminant. A peristaltic pump circulated 250 mL of distilled water or phenol through the reactor at a solution flow rate of 100 mL/min. Adding a 1-mol/L KCl solution adjusted the initial electrical conductivity of the testing solution to 100 $\mu\text{S}/\text{cm}$. 100 glass beads supported with TiO_2 were packed in the reactor as photocatalyst in the plasma/ TiO_2 system. Fig. 3 shows the packed state of the photocatalysts. The formed discharge plasmas do not change in the reaction systems with or without the photocatalysts. Throughout the experiments, O_2 with a 5 L/min flow rate was continuously bubbled into the reactor through the orifices of the stainless-steel ground electrode. Samples were taken for analysis at given intervals. All experiments were carried out under a consistent input power.

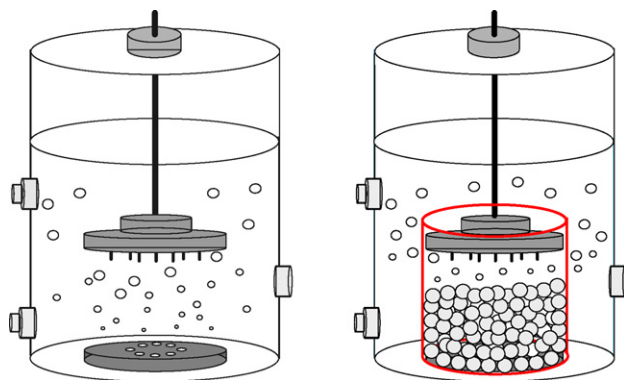


Fig. 3. Schematic diagram of the reactor: (a) without TiO₂ and (b) with TiO₂.

2.5. Analytical procedure

A Hanna EC215 conductivity meter (Italy) and an Orion 828 pH meter (U.S.) measured solution conductivity and pH. The products of phenol degradation and the corresponding change in phenol concentration were determined by HPLC using a LC-10Avp Shimadzu liquid chromatograph equipped with a UV–vis detector and a Shim-pack VP-ODS column with 150 mm length, 4.6 mm diameter, and 4.6 μm particle diameters. 55:45 methanol:water (v/v) at a 0.5 mL/min flow rate ($\lambda = 277$ nm) served as a mobile phase. A Shimadzu TOC-V_{CPH} total organic carbon analyzer determined the total organic carbon (TOC), and a pertitanic acid production method colorimetrically determined the concentration of H₂O₂ in the reaction systems [25]. Potassium ferrioxalate actinometry measured the radiant power of the reaction systems [26].

3. Results and discussion

3.1. Emission spectra of active radicals (\bullet OH and \bullet O)

Because of its higher oxidation potential (2.8 V), the \bullet OH radical is considered to be one of the most important oxidative species for decomposing organic compounds in pulsed discharge systems as well as in TiO₂ photocatalysis systems [13,27]. \bullet O, another oxidative radical (oxidation potential: 2.4 V) discharged causes organic contaminants oxidation. The emission spectra of \bullet OH and \bullet O radicals in the reaction systems hence were recorded to explain the effect of TiO₂ photocatalyst in the pulsed discharge system.

Typical peaks of \bullet OH generated during discharge appeared at 306 nm, 309 nm, and 313 nm (Sun et al., 1997); the corresponding transitions are $A^2\Sigma^+ \rightarrow X^2\Pi$, $A^2\Sigma^+(v' = 0) \rightarrow X^2\Pi(v'' = 0)$ and $A^2\Sigma^+(v' = 1) \rightarrow X^2\Pi(v'' = 1)$, while the representative peak of \bullet O is at 777 nm ($3p^5P \rightarrow 3s^5S$) [15]. Fig. 4(a) and (b) presents the relative emission intensity of \bullet OH at 313 nm and \bullet O at 777 nm. The relative emission intensities of \bullet OH and \bullet O radicals in phenol solutions and distilled water were also recorded separately and equally to explore the consumption of oxidative species by organic compounds in the two reaction systems of plasma alone and plasma coupled with TiO₂ photocatalysis. The integration times

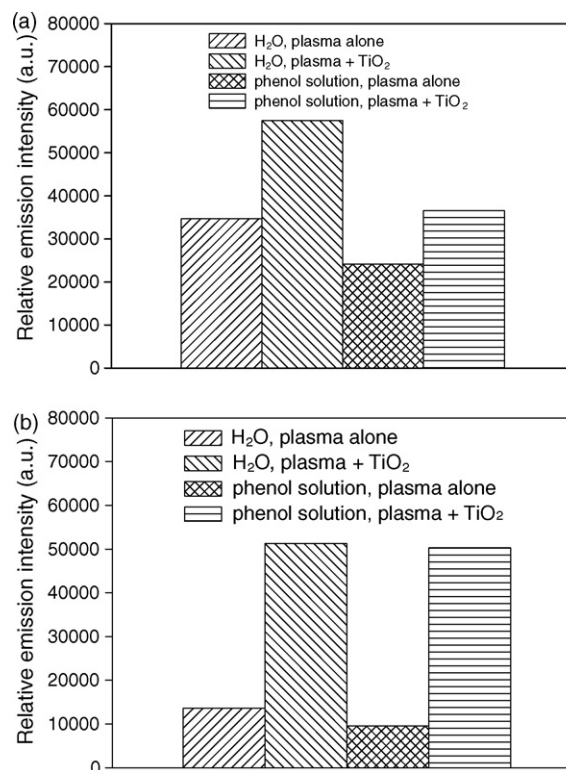
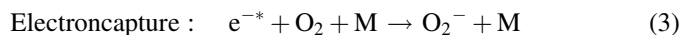
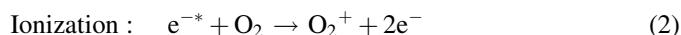
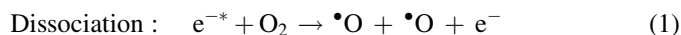


Fig. 4. Relative emission intensities of oxidative radicals in distilled water and phenol solutions: (a) \bullet OH (313 nm) and (b) \bullet O (777 nm).

for data collection of \bullet OH and \bullet O radicals by spectrograph were 4000 ms and 500 ms.

Comparison of the relative emission intensities of \bullet OH at 313 nm and \bullet O at 777 nm. The relative emission intensities of \bullet OH and \bullet O in the plasma-photocatalysis system were higher than in the plasma alone system. Hence, TiO₂ photocatalysis must have certain beneficial effects on the increased oxidative species generation in the pulsed discharge system.

High-energy electrons (e^{-*}) produced in a pulsed discharge electric field can collide with ambient gas molecules, initiating excitation, dissociation, electron capture or ionization. With O₂ as a bubbling gas, the following reactions could take place [9]:

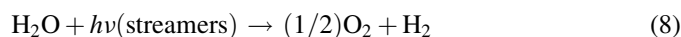
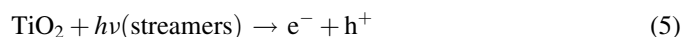


whereas reaction induced by a pulsed discharge in an aqueous phase could be initiated as follows [13]:



The formed radicals of reactions (1)–(4), particularly \bullet O and \bullet OH, play a major role in destroying pollutants in a pulsed discharge plasma system. In the plasma/TiO₂ system, the UV light (included in the streamers) in the plasma channels would induce photocatalytic reactions of TiO₂. The primary reactions

are given by [27]:



It can be seen from reaction (8) that O_2 could be formed when the streamer irradiated on the TiO_2 photocatalyst, whereas $\bullet\text{O}$ could be generated by O_2 through the effect of the pulsed discharge electric field (reaction (1)). The above reactions caused an increase in the relative emission intensity of $\bullet\text{O}$ in the plasma- TiO_2 photocatalysis system relative to that of the plasma alone system. The increase of O_3 concentration can also be resulted in this way. While the increased intensity of $\bullet\text{OH}$ might be due to the enhanced electric field in the plasma/ TiO_2 system.

From Fig. 4(a), it can also be indicated that a lower emission intensity of $\bullet\text{OH}$ in the phenol solutions than in the distilled water under the same conditions in both the plasma alone and plasma/ TiO_2 systems. This suggests that the reactions between $\bullet\text{OH}$ and organic compounds could decrease $\bullet\text{OH}$ radicals. However, the similar conclusion cannot be obtained clearly for $\bullet\text{O}$ (shown in Fig. 4(b)), especially in the case of plasma/ TiO_2 system. This result might be due to the lower reaction activity of $\bullet\text{O}$ than $\bullet\text{OH}$. Furthermore, the emission intensity of $\bullet\text{OH}$ and $\bullet\text{O}$ in the plasma/ TiO_2 system was evidently higher than that in the plasma alone system, attributable to the TiO_2 photocatalysis induced by the streamer.

3.2. Hydrogen peroxide (H_2O_2) formation

Quantitative analysis of $\bullet\text{OH}$ has always been very difficult because of its transitory life. However, $\bullet\text{OH}$ itself could combine to form H_2O_2 ; the following reaction shows this primary way of forming H_2O_2 in aqueous solutions [13,28]:



Hence, measuring the H_2O_2 generated during the reaction process is an indirect way to determine the amount of $\bullet\text{OH}$. In this study, H_2O_2 concentrations during the course of pulsed discharge were measured in the distilled water and phenol solutions with and without supported TiO_2 . Fig. 5 illustrates concentration curves for H_2O_2 generation in the two reaction systems.

Consistent with the obtained spectral detection, these curves clearly show that more H_2O_2 was generated in the coupling system of the pulsed discharge plasma and TiO_2 photocatalysis, either with distilled water or with phenol solutions. Furthermore, phenol consumed the $\bullet\text{OH}$ in the reaction system, leading to a later decline of H_2O_2 concentrations in phenol solutions. TiO_2 photocatalysis induced by streamers was considered the main source of forming more oxidative species to oxidize organic compounds.

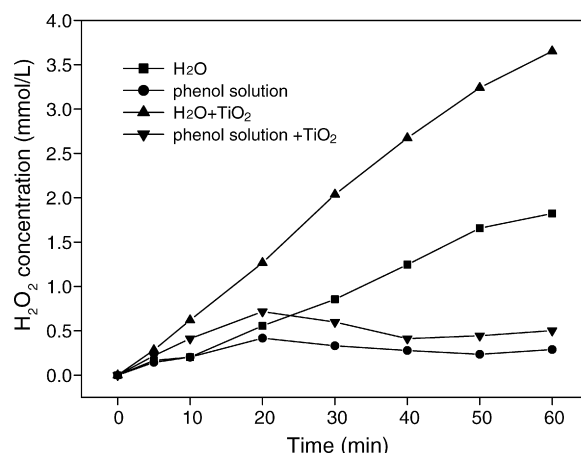


Fig. 5. Formation of H_2O_2 in distilled water and phenol solutions with and without TiO_2 .

3.3. Radiant power

Emission spectroscopy analysis revealed that streamers formed during pulsed discharge in water range widely from ultraviolet to near infrared wavelengths [15]. Lukeš has evaluated the intensity of UV light (200–300 nm) emitted in the pulsed corona discharge system by chemical actinometry using potassium ferrioxalate ($\text{K}_3\text{Fe}(\text{C}_2\text{O}_4)_3$) [26]. In the method, the measuring solution fills in the whole reaction system. In order to explain the existence of streamer in the pulsed discharge plasma system in quantity, radiant powers of light with wavelengths of 200–500 nm in the two systems (plasma alone and plasma/ TiO_2 systems) were measured using an identical method. The radiant power in the plasma alone system was 5.38 mW, lower than the 7.22 mW of the plasma/ TiO_2 system. This result might be used to confirm the existence of streamer in the plasma system as well as the photocatalysis in the plasma/ TiO_2 system.

3.4. Phenol degradation

Fig. 6 illustrates phenol oxidation in the plasma alone system and plasma/ TiO_2 systems. The corresponding kinetic pathway of phenol degradation followed the pseudo-first-order

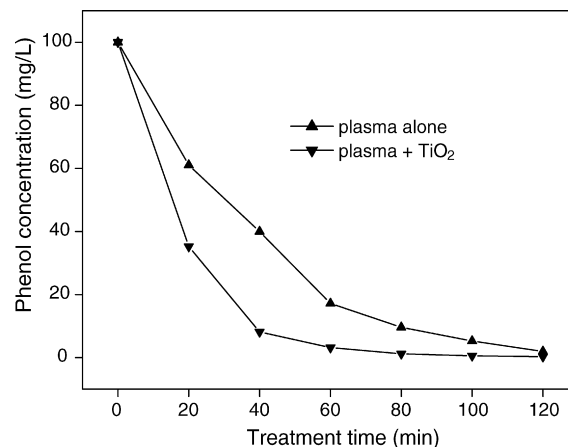


Fig. 6. Phenol concentrations in plasma systems with and without TiO_2 .

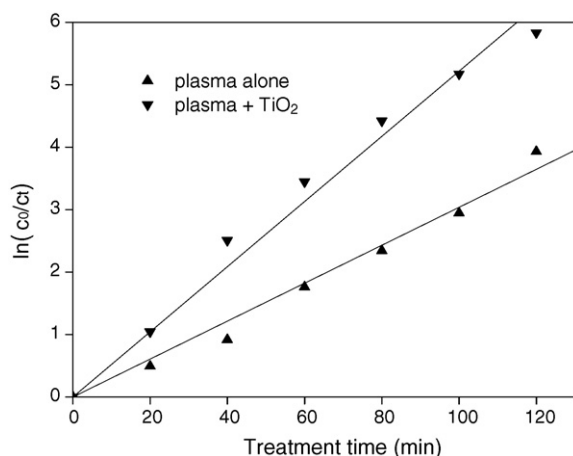


Fig. 7. Kinetics of phenol degradation in plasma systems with and without TiO_2 .

law (Fig. 7). Table 1 summarizes the kinetic parameters of phenol degradation and the energy efficiencies of phenol conversion (G_{50}) in the reaction systems.

Figs. 6 and 7 indicate that the degradation reactions of phenol obeyed the pseudo-first-order law with good relativity; the decomposition velocity of phenol in the plasma/ TiO_2 system was higher than that in the plasma alone system under the same experimental conditions. The kinetic parameters presented in Table 1 include a reaction kinetic constant of phenol oxidation in the plasma/ TiO_2 system ($k = 5.2 \times 10^{-2} \text{ min}^{-1}$) about 1.7 times higher than that in the plasma alone system ($k = 3.1 \times 10^{-2} \text{ min}^{-1}$). Furthermore, the energy efficiency of phenol removal (G_{50}) in the plasma/ TiO_2 system reached $23.2 \times 10^{-9} \text{ mol/J}$, higher than the value ($14.6 \times 10^{-9} \text{ mol/J}$) in the plasma alone system. The energy efficiency of phenol conversion reported by Šunka et al. [28] reached $4.2 \times 10^{-10} \text{ mol/J}$, whereas G_{50} values achieved under different experimental conditions in the research of Sun et al. [7] were $1.0 \times 10^{-9} \text{ mol/J}$, $2.3 \times 10^{-9} \text{ mol/J}$, and $6.9 \times 10^{-9} \text{ mol/J}$. Comparing the G_{50} values obtained in our research with those of others, our multi-needle-to-plate pulsed discharge system had a higher energy efficiency, especially in the coupling system of pulse discharge plasma and TiO_2 photocatalysis. Adding supported TiO_2 to the plasma system aids in the degradation of organic compounds.

To further illustrate the effect of TiO_2 photocatalysis on phenol degradation in the pulsed discharge plasma system, the amounts of the main byproducts (e.g. catechol, hydroquinone, and benzoquinone) formed during phenol oxidation were measured, with and without the presence of TiO_2 . Fig. 8 shows that maximum concentrations of the three main byproducts in the plasma alone system higher than those in the plasma/ TiO_2

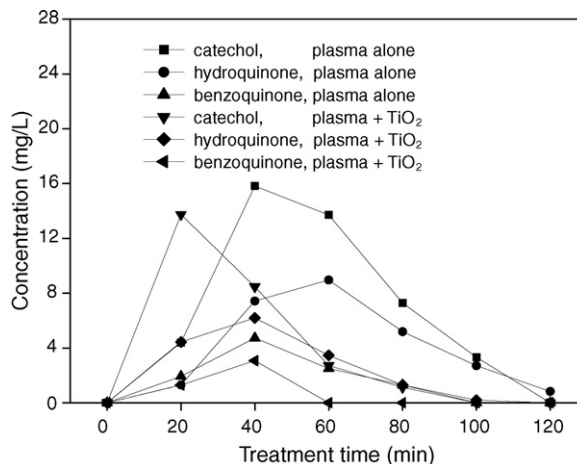


Fig. 8. Byproducts generation in plasma systems with and without TiO_2 .

system. Catechol and hydroquinone reached the maximum concentrations earlier in the plasma/ TiO_2 system, whereas benzoquinone reached its maximum concentration almost at the same time in the two discharge systems. In addition, the TOC removal rate increased from 55.2% in the plasma alone system to 66.1% in the plasma/ TiO_2 system, demonstrating that more phenol molecules were mineralized to smaller organic molecules or to carbon dioxide in the plasma/ TiO_2 system. Recall the previous spectral analysis of Section 3.1, in which TiO_2 photocatalysis induced by streamers was the main reason for the improvement of oxidative species generation.

3.5. Role of $\bullet\text{OH}$ radicals

A study of hydroxyl radical scavengers on organic compound removal permitted an evaluation of the important role of active $\bullet\text{OH}$ radicals in AOPs [14,29]. *N*-Butanol as the hydroxyl radical scavenger tested the effect of $\bullet\text{OH}$ on organic compound degradation; $\bullet\text{OH}$ generated in the photocatalytic reaction in the plasma/ TiO_2 system was also detected in this way. Table 2 summarizes the kinetic parameters and energy efficiencies of phenol oxidation with different amounts of *n*-butanol added (0 mmol/L, 0.1 mmol/L, 0.5 mmol/L, 1.0 mmol/L, and 5.0 mmol/L). The treatment time is 60 min.

Table 2 illustrates that the reaction kinetic constant of phenol oxidation decreased with increasing of concentrations of *n*-butanol added to the pulsed discharge or plasma-photocatalysis system. In addition, the kinetic parameters and energy efficiencies achieved in the plasma/ TiO_2 system were higher than those in the plasma alone system, except when 5.0 mmol/L *n*-butanol was added to the pulsed discharge system.

Table 2 further suggests that the addition of hydroxyl radical scavengers in a pulsed discharge system could partially prevent the reaction between $\bullet\text{OH}$ and phenol. Moreover, when the *n*-butanol (5.0 mmol/L) added exceeded the amount needed to consume all $\bullet\text{OH}$ generated either by pulsed discharge or by TiO_2 photocatalysis, the kinetic constants of phenol degradation in the reaction system with and without TiO_2 became consistent. Clearly, generated $\bullet\text{OH}$ plays a significant role

Table 1
Kinetic constant (k) and G_{50} of phenol in different reaction systems

Reaction system	$k (\times 10^{-2} \text{ min}^{-1})$	R^2	$G_{50} (\times 10^{-9} \text{ mol/J})$
Plasma alone	3.1	0.988	14.6
Plasma-photocatalysis	5.2	0.986	23.2

Table 2

Kinetic constant (k) and G_{50} of phenol decomposition under various radical scavenger additions

Reaction system	Concentration of additive (<i>n</i> -butanol) (mmol/L)	k ($\times 10^{-2}$ min $^{-1}$)	R^2	G_{50} ($\times 10^{-9}$ mol/J)
Plasma alone	0	2.4	0.970	11.6
	0.1	1.8	0.920	8.6
	0.5	1.5	0.891	7.1
	1.0	1.2	0.920	5.9
	5.0	1.0	0.984	4.8
Plasma-photocatalysis	0	6.1	0.972	27.3
	0.1	3.2	0.943	14.2
	0.5	3.0	0.926	13.6
	1.0	2.5	0.941	11.1
	5.0	1.0	0.907	4.6

during the courses of pulsed discharge and TiO₂ photocatalytic reactions in the hybrid gas–liquid system, and more \bullet OH can be produced by coupling pulsed discharge plasma with TiO₂ photocatalyst.

4. Conclusions

In summary, the developed pulsed discharge system coupled with TiO₂ photocatalysis had a synergistic effect on oxidative species generation and phenol degradation. More oxidative species such as \bullet OH, \bullet O and H₂O₂, were formed in the synergistic system of pulsed discharge plasma and TiO₂ photocatalysis, leading to an increase of phenol degradation in the plasma/TiO₂ system; higher energy efficiency were also achieved. The coupling system need not use a lamp house as an external source to induce the photocatalysis of TiO₂, thereby increasing the decomposition of organic compounds and the energy efficiency.

Acknowledgments

The authors would like to thank the National Nature Science Foundation of China (project Nos. 20377006 and 20337020) and National Science Fund for Distinguished Young Scholars of China (project No. 20525723) for their financial support.

References

- [1] J.S. Clements, M. Sato, R.H. Davis, IEEE Trans. Ind. Appl. IA-23 (1987) 224–235.
- [2] A.K. Sharma, B.R. Locke, P. Arce, W.C. Finney, Hazard. Waste Hazard. Mater. 10 (1993) 209–219.
- [3] D.M. Willberg, P.S. Lang, R.H. Hochemer, A. Kratel, M.R. Hoffmann, Environ. Sci. Technol. 30 (1996) 2526–2534.
- [4] M. Tezuka, M. Iwasaki, Thin Solid Films 316 (1998) 123–127.
- [5] B. Sun, M. Sato, J.S. Clements, J. Phys. D: Appl. Phys. 32 (1999) 1908–1915.
- [6] W.F.L.M. Hoebe, E.M. van Veldhuizen, W.R. Rutgers, C.A.M.G. Cramers, G.M.W. Kroesen, Plasma Sources Sci. Technol. 9 (2000) 361–369.
- [7] B. Sun, M. Sato, J.S. Clements, Environ. Sci. Technol. 34 (2000) 509–513.
- [8] A.K. Sharma, G.B. Josephson, D.M. Camaioni, S.C. Goheen, Environ. Sci. Technol. 34 (2000) 2267–2272.
- [9] M.A. Malik, A. Ghaffar, S.A. Malik, Plasma Sources Sci. Technol. 10 (2001) 82–91.
- [10] A.T. Sugiarto, T. Ohshima, M. Sato, Thin Solid Films 407 (2002) 174–178.
- [11] A.T. Sugiarto, S. Ito, T. Ohshima, M. Sato, J.D. Skalny, J. Electrostat. 58 (2003) 135–145.
- [12] E. Njatawidjaja, A.T. Sugiarto, T. Ohshima, M. Sato, J. Electrostat. 63 (2005) 353–359.
- [13] A.A. Joshi, B.R. Locke, P. Arce, W.C. Finney, J. Hazard. Mater. 41 (1995) 3–30.
- [14] M. Sato, T. Ohgiyama, J.S. Clements, IEEE Trans. Ind. Appl. 32 (1996) 106–112.
- [15] B. Sun, M. Sato, J.S. Clements, J. Electrostat. 39 (1997) 189–202.
- [16] B. Sun, M. Sato, A. Harano, J.S. Clements, J. Electrostat. 43 (1998) 115–126.
- [17] A.T. Sugiarto, M. Sato, Thin Solid Films 386 (2001) 295–299.
- [18] P. Lukeš, M. Clupek, V. Babický, V. Janda, P. Sunka, J. Phys. D: Appl. Phys. 38 (2005) 409–416.
- [19] M.J. Kirkpatrick, B.R. Locke, Ind. Eng. Chem. Res. 44 (2005) 4243–4248.
- [20] K. Honda, A. Fujishima, Nature 238 (1972) 37–38.
- [21] P. Lukeš, M. Clupek, P. Sunka, F. Peterka, T. Sano, N. Negishi, S. Matsuzawa, K. Takeuchi, Res. Chem. Intermed. 31 (2005) 285–294.
- [22] X. Hao, M. Zhou, Y. Zhang, L. Lei, Plasma Chem. Plasma Process 26 (2006) 455–468.
- [23] H. Wang, J. Li, X. Quan, J. Electrostat. 64 (2006) 416–421.
- [24] M.A. Anderson, M.J. Gieselman, Q. Xu, J. Membr. Sci. 39 (1988) 243–258.
- [25] R.M. Sellers, Analyst 105 (1980) 950–954.
- [26] P. Lukeš, Water treatment by pulsed streamer corona discharge, Ph.D. Thesis, Institute of Plasma Physics AS CR, 2001.
- [27] A. Fujishima, T.N. Rao, D.A. Tryk, J. Photochem. Photobiol. C: Photochem. Rev. 1 (2000) 1–21.
- [28] P. Šunka, V. Babický, M. Clupek, P. Lukeš, M. Šimek, J. Schmidt, M. Černák, Plasma Sources Sci. Technol. 8 (1999) 258–265.
- [29] Y.S. Chen, X.S. Zhang, Y.C. Dai, W.K. Yuan, Sep. Purif. Technol. 34 (2004) 5–12.